Testing Lorentz invariance with *Fermi* Gamma-Ray Bursts

Frédéric Piron

Laboratoire Univers et Particules de Montpellier (CNRS / IN2P3)

Probing quantum spacetime with
Astrophysical Sources : the CTA era and beyond
(Paris, 11/29/2017)

Outline

- **GRB observations with *Fermi***
- **Studies of deterministic LIV**
- **Stochastic LIV**

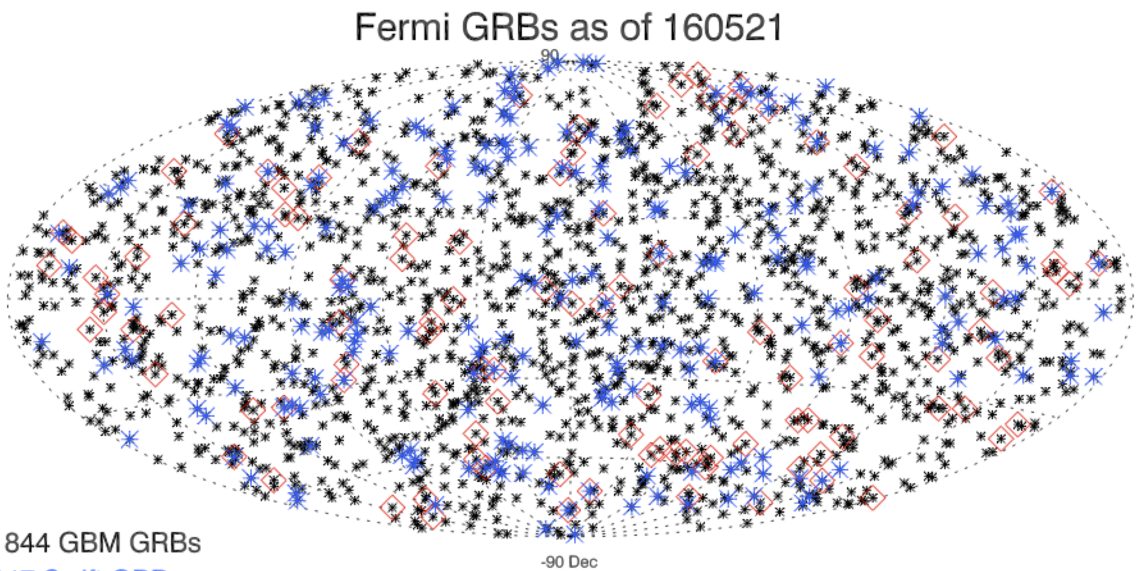
The instruments onboard *Fermi*

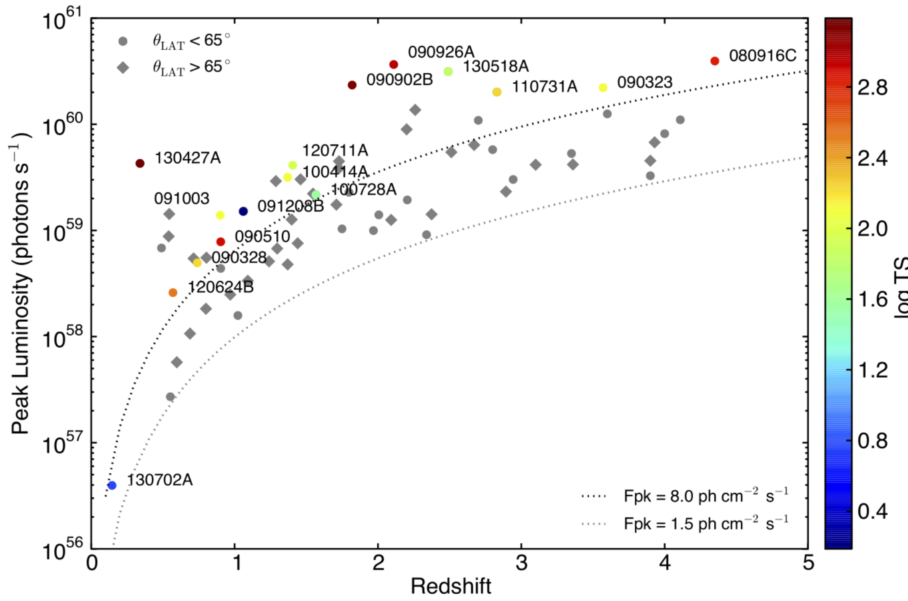
Atwood et al. 2009, ApJ 697, 1071
Meegan et al. 2009, ApJ 702, 791

- **Large Area Telescope (LAT)**
  - Large field of view (2.4 sr @ 1 GeV)
  - Sees the entire sky every 3 hours
  - 20 MeV to >300 GeV
  - Onboard and ground burst triggers
  - Localization, spectroscopy
- **Gamma-ray Burst Monitor (GBM)**
  - Sees the entire unocculted sky (>9.5 sr)
  - 8 keV to 40 MeV
  - 12 NaI detectors (8 keV to 1 MeV)
    - Onboard trigger, onboard and ground localizations, spectroscopy
  - 2 BGO detectors (150 keV to 40 MeV)
    - Spectroscopy

A broad energy range and sky coverage to study GRBs

Fermi GRB statistics and catalogs





Paciesas et al. 2012, ApJS 199, 18
Goldstein et al. 2012, ApJS 199, 19
Von Kienlin et al. 2014, ApJS 211, 13
Gruber et al. 2014, ApJS 211, 12
Yu et al. 2016, A&A 588, 135
P. Narayana Bhat et al. 2016, ApJS 223, 28

- **The GBM detected > 2000 bursts (~250 / yr)**
  - Including 17% of short GRBs

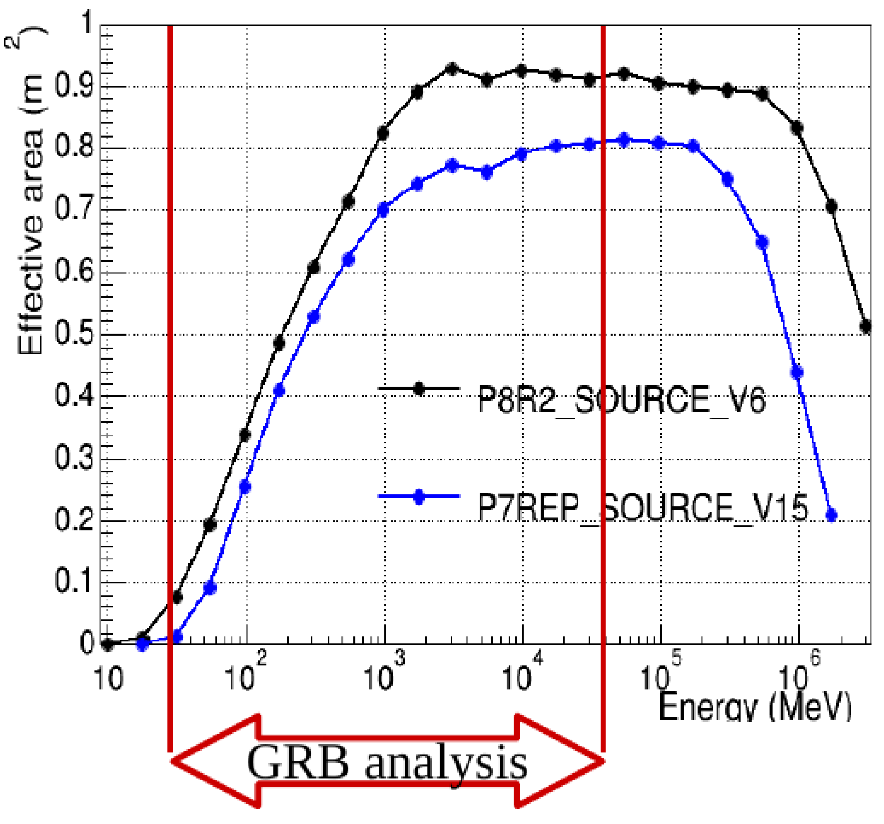
- **The LAT detects ~10% of GBM GRBs in its field-of-view above 100 MeV**
  - LAT bright GRBs with good localizations are all followed-up by Swift
  - From z=0.145 (GRB 130702A) to z=4.35 (GRB 080916C)
  - Flux-limited sub-sample of the normal GRB population

- **First LAT GRB catalog: 3 years, 35 GRBs (30 long, 5 short)** *Ackermann et al. 2013, ApJS 209, 11*
  - 10 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C)

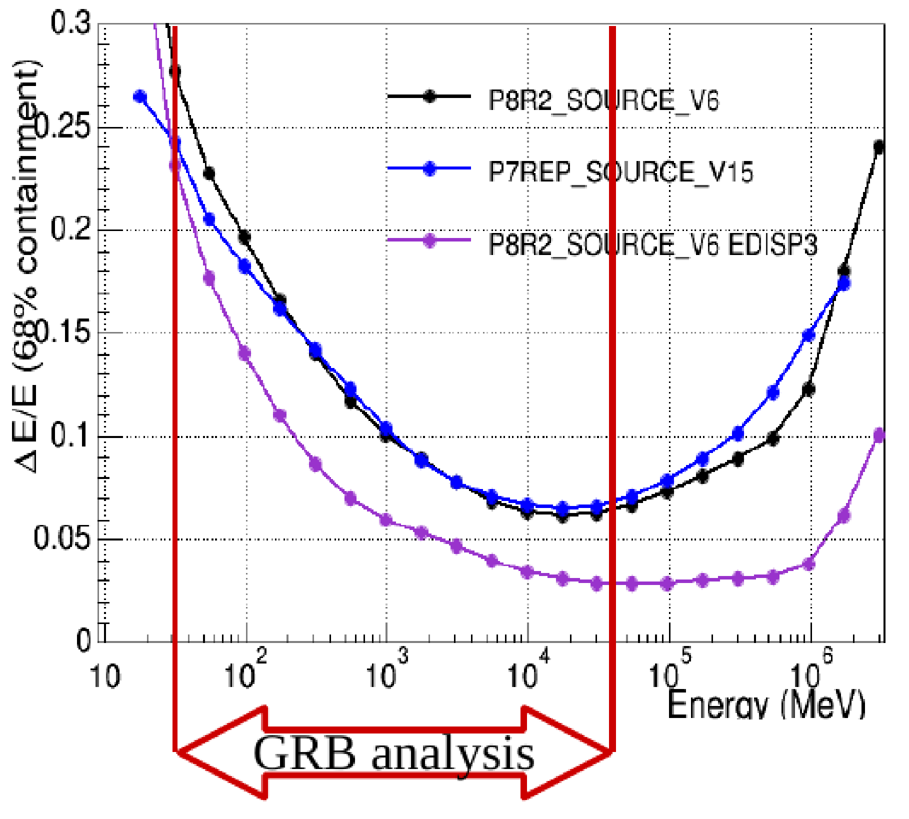
Improved performance with LAT Pass 8 data

- **Pass 6 data:** released in August 2009 (pre-flight)
- **Pass 7 data:** released in August 2011 (fix for so-called “ghosts”)
- **Pass 8 data:** released in June 2015
  - New event reconstruction and classification algorithms → larger effective area, better PSF, lower energy threshold for spectral analysis

On-axis effective area

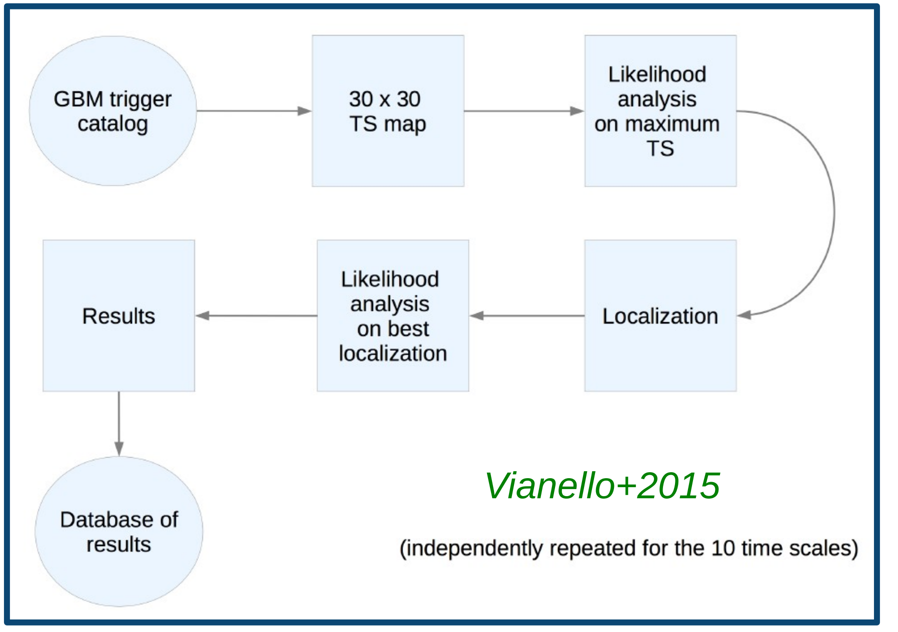


Acceptance-weighted energy resolution

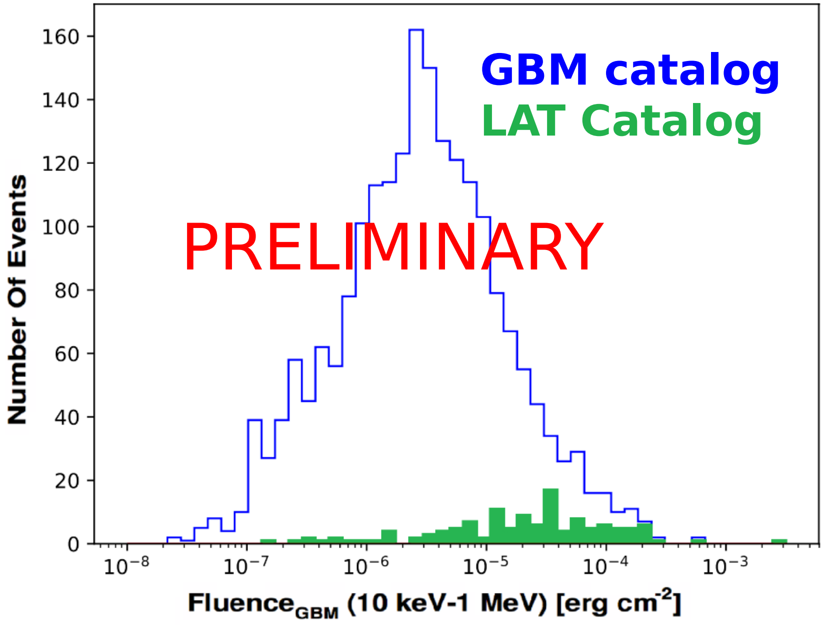


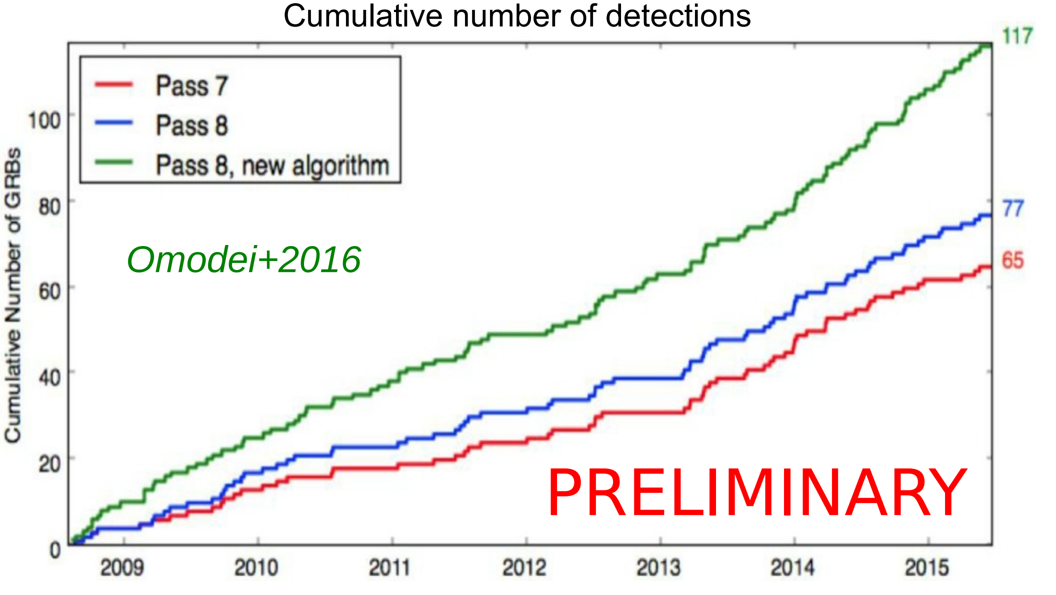
Towards the 2nd LAT GRB catalog

- **New scheme to detect GRBs**
  - Overcomes large systematic error on the GBM localization
  - Searches on different time scales
- **Increase by >50% of the LAT detection rate**
  - >130 GRBs in 9 years, including ~12 SGRBs
  - Also evident in published GCNs!



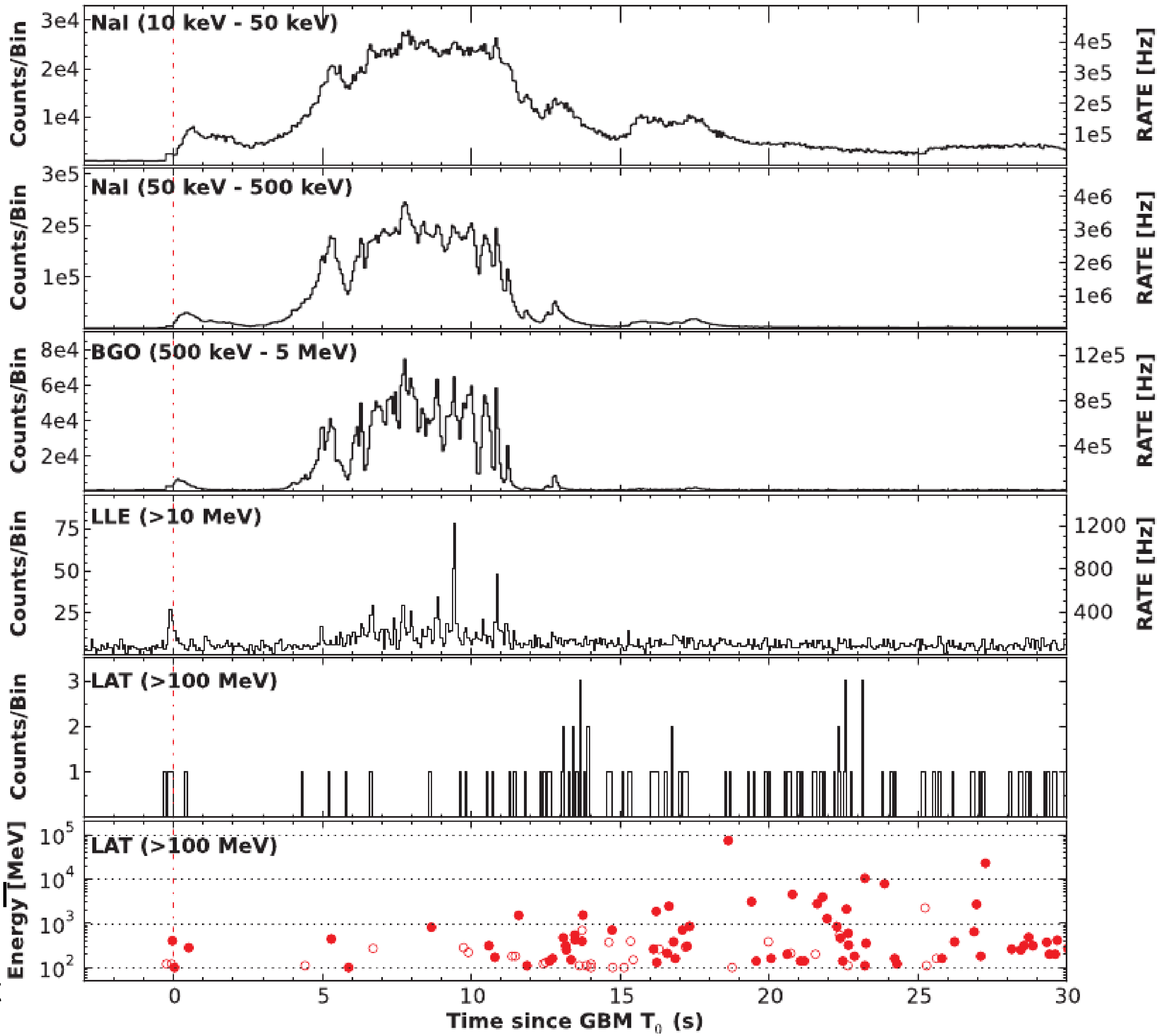
Among the brightest and most fluent GBM GRBs





GRB 130427A multi-detector light curve

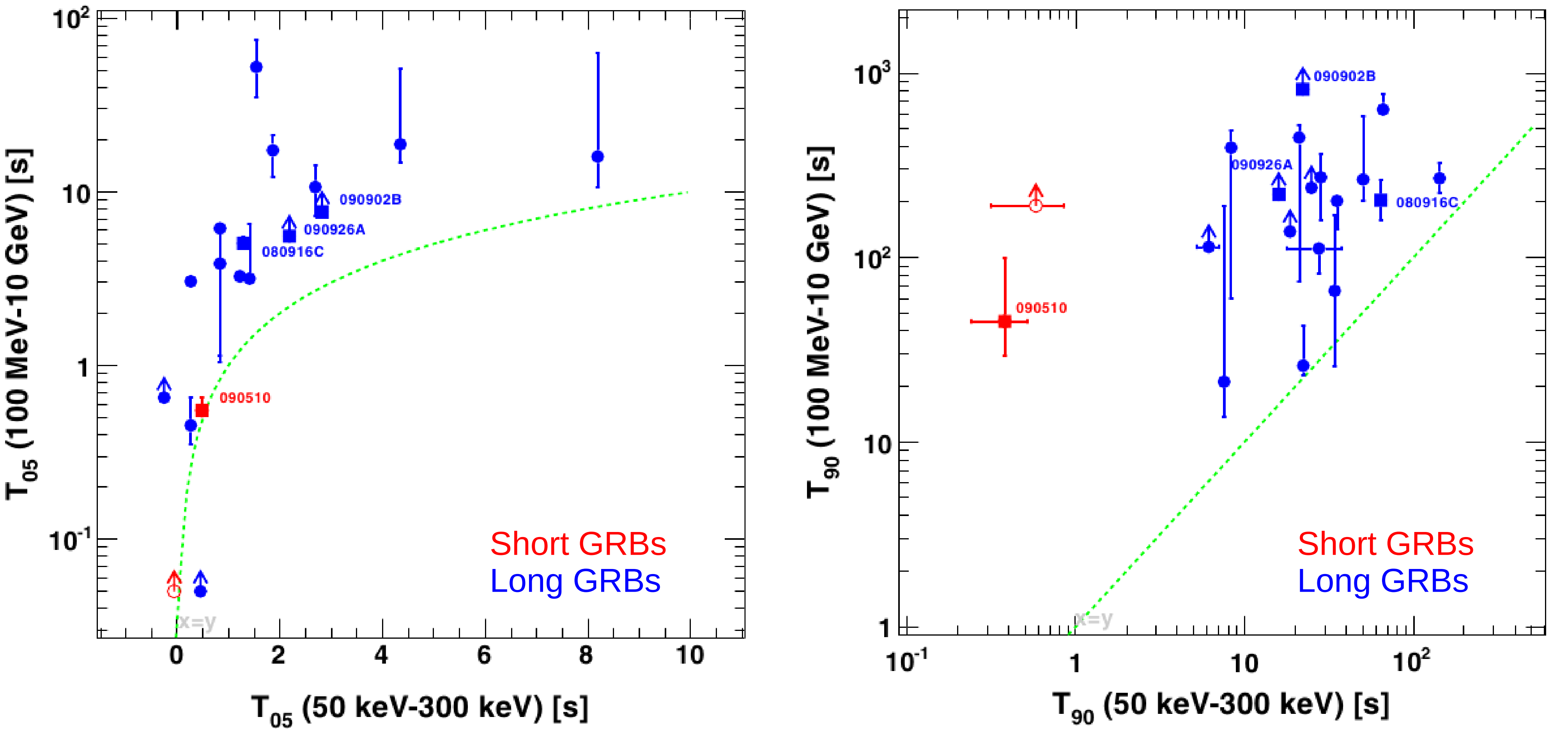
- **Highest γ-ray fluence ever ($> 10^{-3}$ erg cm^{-2})**
- **$E_{iso} = 1.4 \times 10^{54}$ erg**
- **Brightest LAT GRB**
  - >500 photons >100 MeV
  - 15 photons >10 GeV
- **Unlike other bright LAT GRBs, the LAT >100 MeV emission is temporally distinct from the GBM emission**
- **LAT >100 MeV emission is delayed and temporally extended**
  - Delay ~10 s, continues well after the prompt phase
  - 73 GeV photon detected at T_0+19 s



Ackermann et al. 2014, Science 343, 42

Temporal properties

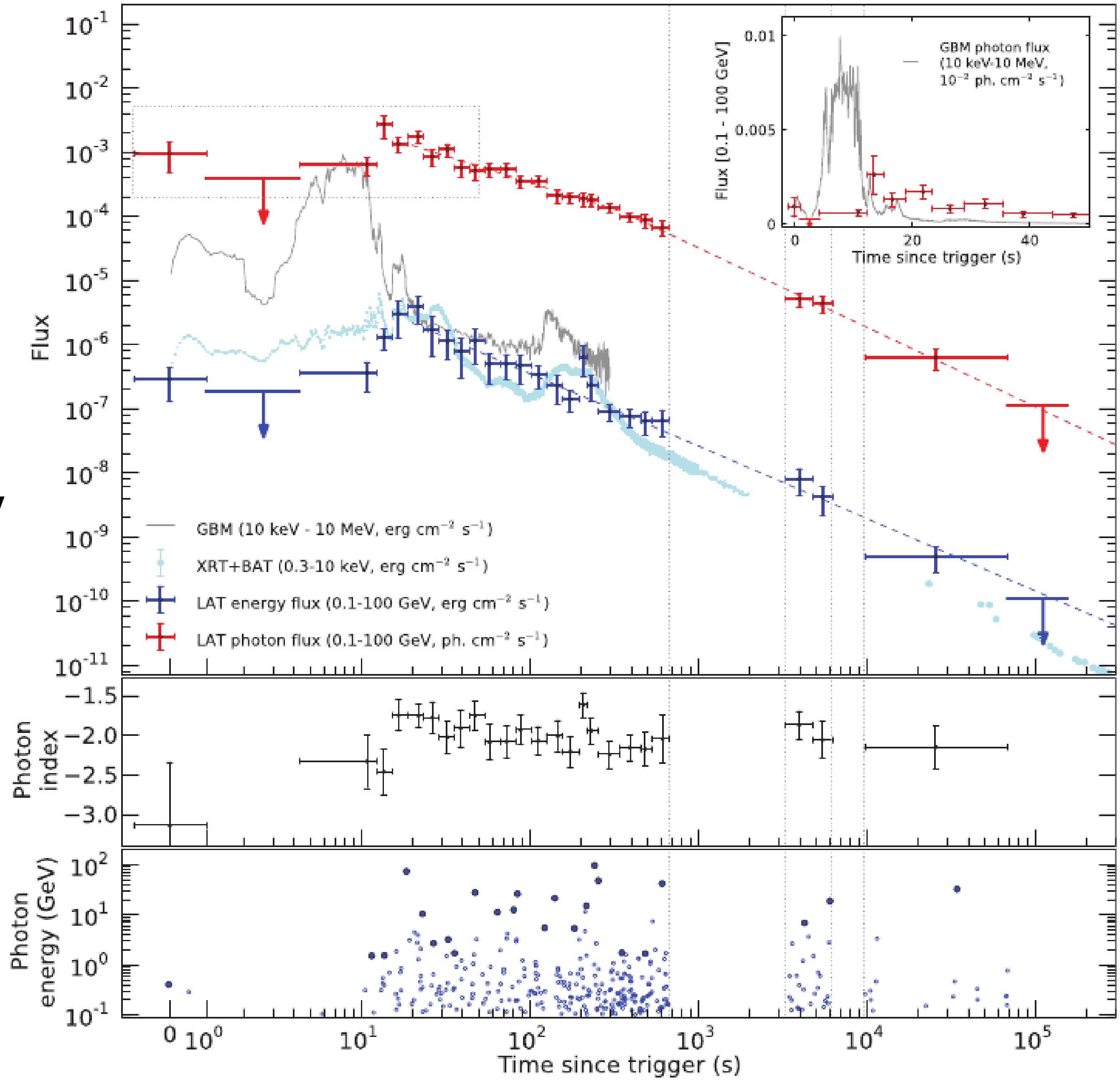
Ackermann et al. 2013, ApJS 209, 11



- **The delay in the onset of the >100 MeV emission and its temporal extension are common to the vast majority of LAT-detected GRBs**
- **Suggests independent emission processes at keV-MeV and >100 MeV energies**

GRB 130427A afterglow in X-rays and γ-rays

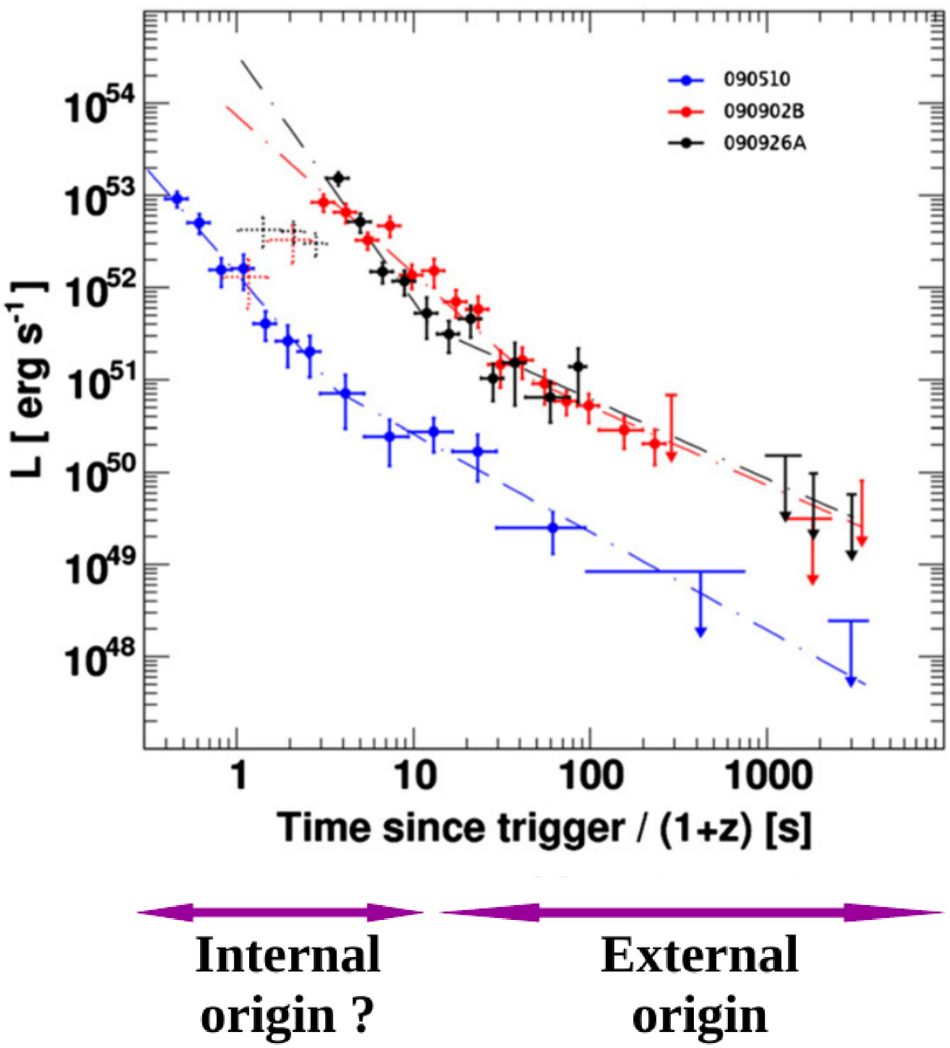
- **Brightest X-ray afterglow ever detected**
- **Longest-lived gamma-ray emission: LAT emission detected for 19 hours**
- **LAT light curve is ~smooth**
- **LAT spectrum described by a power law at all times**
  - Spectral index $\alpha_{EX} \sim -2$
- **Common features between LAT and lower energy light curves**
- **Record breaking 95 GeV photon at T_0+244 s**



Ackermann et al. 2014, Science 343, 42

Two successive phases of the GeV emission

Ackermann et al. 2013, ApJS 209, 11



- **Luminosity >100 MeV: broken power-law decay in 3 cases**

  → internal origin of the GeV early emission?

- **E.g., GRB 090926A:**
  - Temporal break Tb ~ T0+40 s (observer frame)
  - Break time well after the end of the prompt MeV emission (T0+22 s)

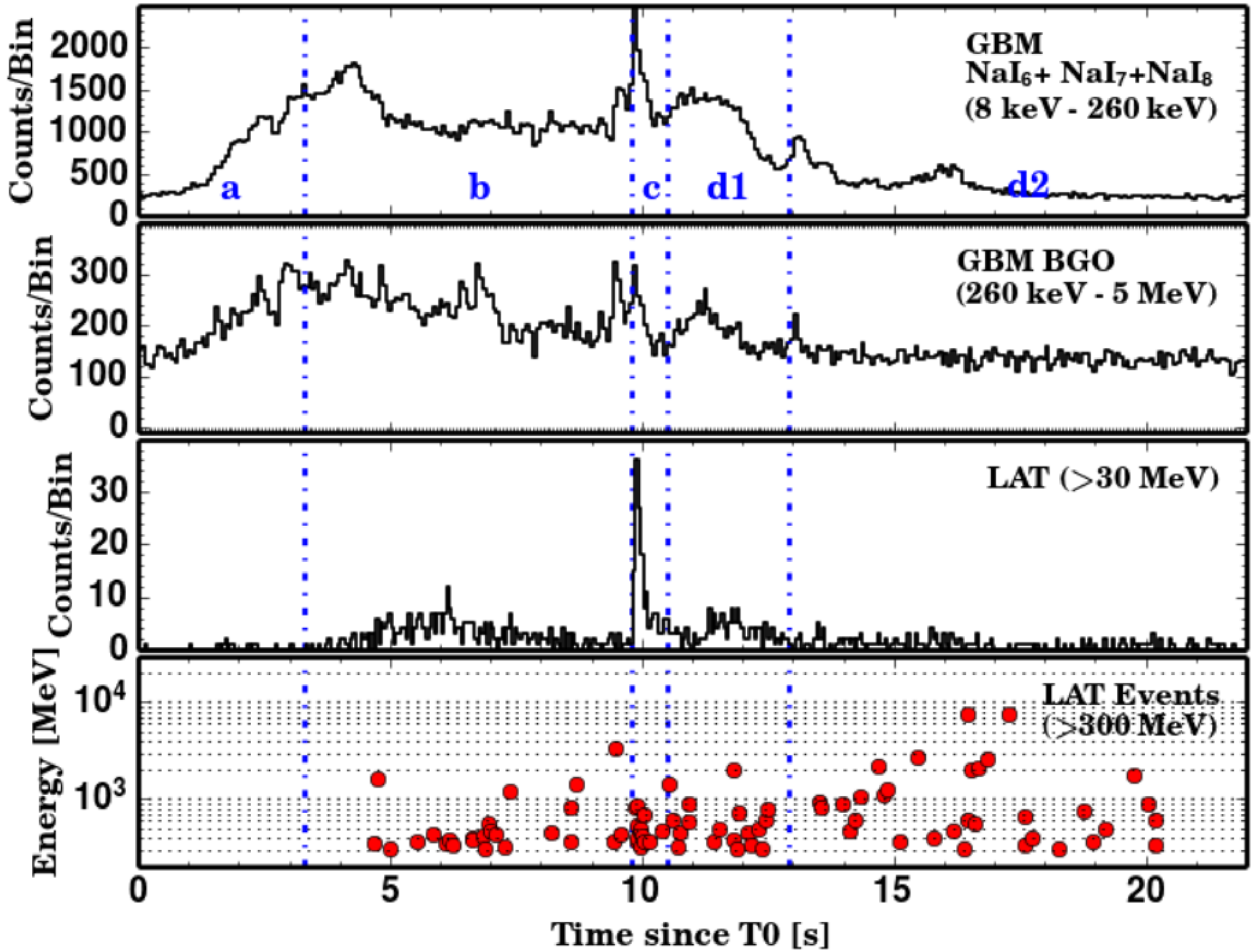
- **At late times : photon index ~ -2 and temporal index ~1 → synchrotron emission from a blast wave in adiabatic expansion**

- **Disentangling both contributions <u>needs time-resolved spectra AND variability studies</u>**

GRB 090926A prompt light curve

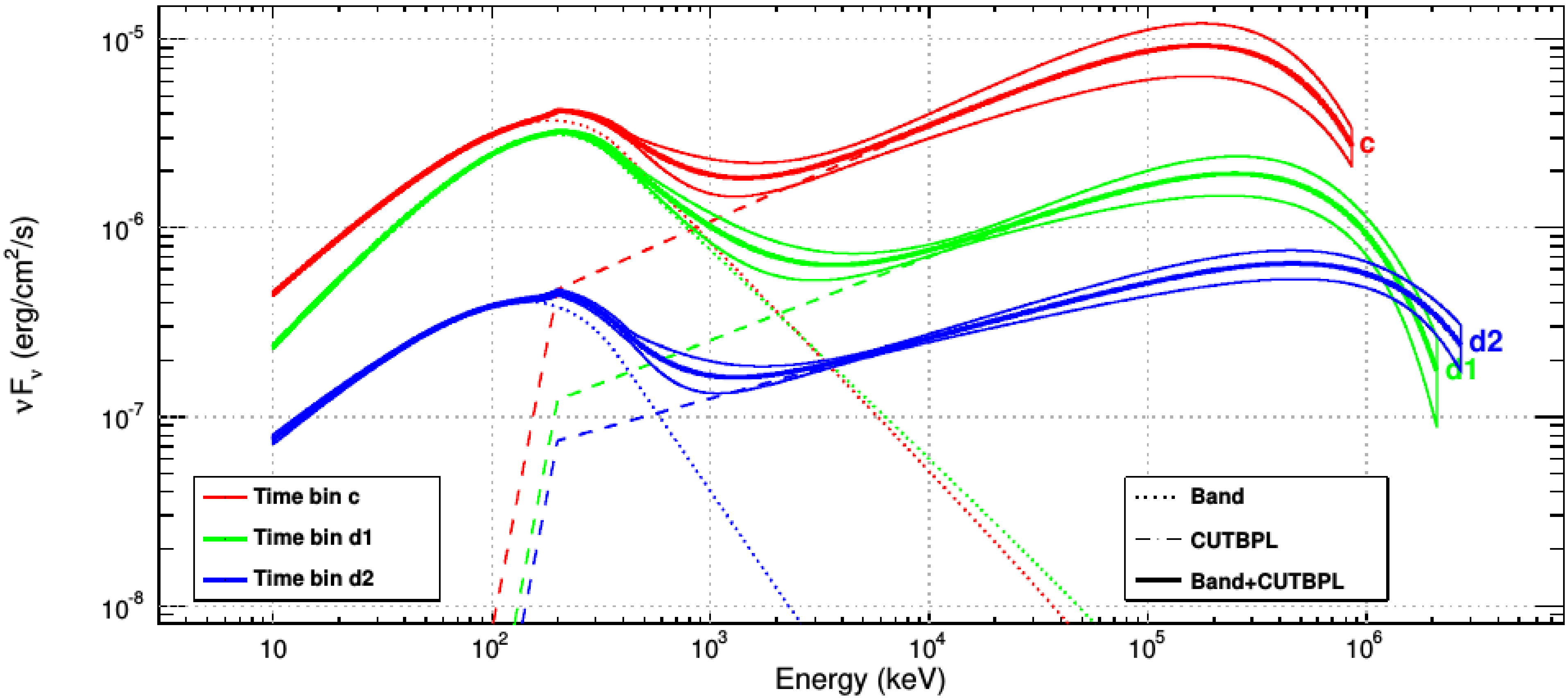
- **Fluence = 2.2 x 10^{-4} erg cm^{-2}**
- **E_{iso} = 2.2 x 10^{54} erg**
- **Delay ~ 4.5 s**
- **Temporal extension (210 s in the LAT)**
- **Correlated variability in various bands with a sharp spike at T_0+10 s**
- **All energy ranges synchronized (<50 ms)**
- **→ Internal origin of the early GeV emission?**

Yassine et al. 2017, A&A 606, 93



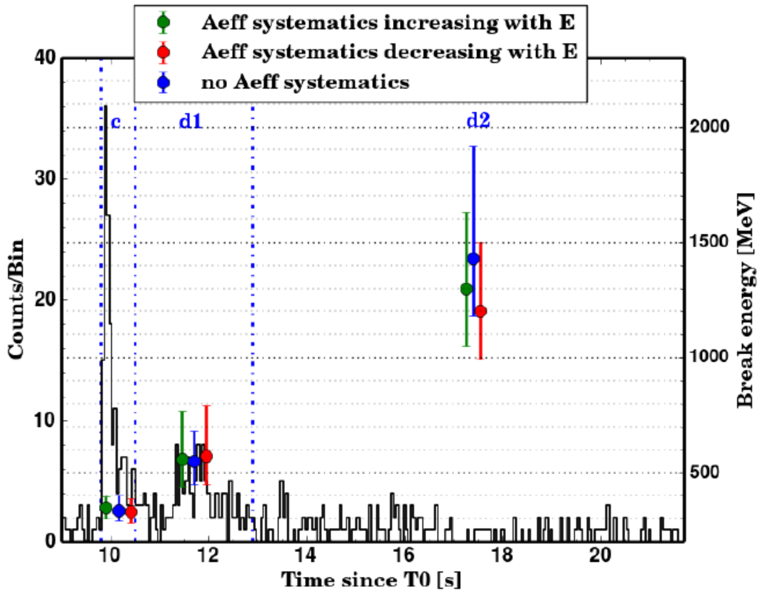
GRB 090926A prompt spectrum

Yassine et al. 2017, A&A 606, 93



Time bins	c [9.8 s, 10.5 s]	d1 [10.5 s, 12.9 s]	d2 [12.9 s, 21.6 s]
Break energy (GeV)	0.34 -0.05 +0.07	0.55 -0.10 +0.13	1.44 -0.25 +0.49
Significance (Nσ)	7.6	4.4	5.1

GRB 090926A: jet speed and emission radii

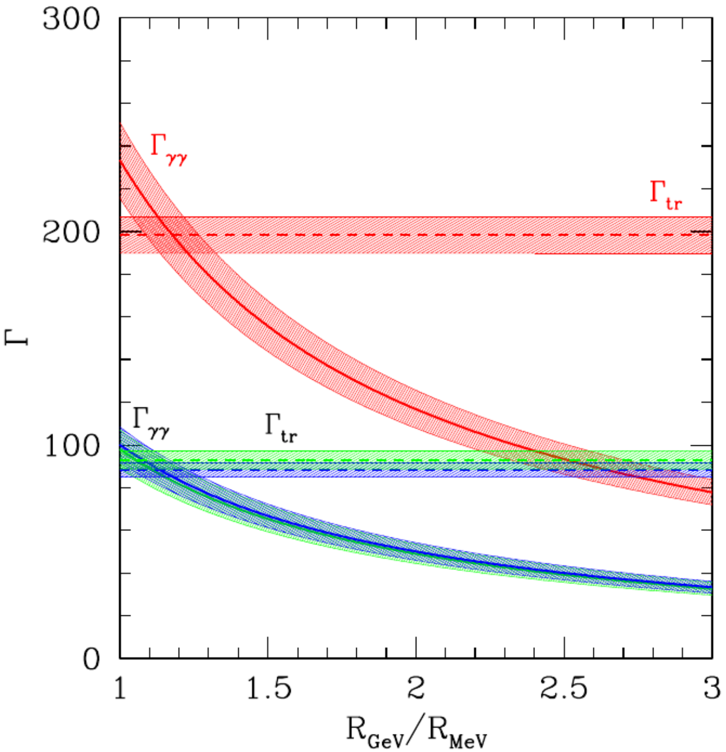


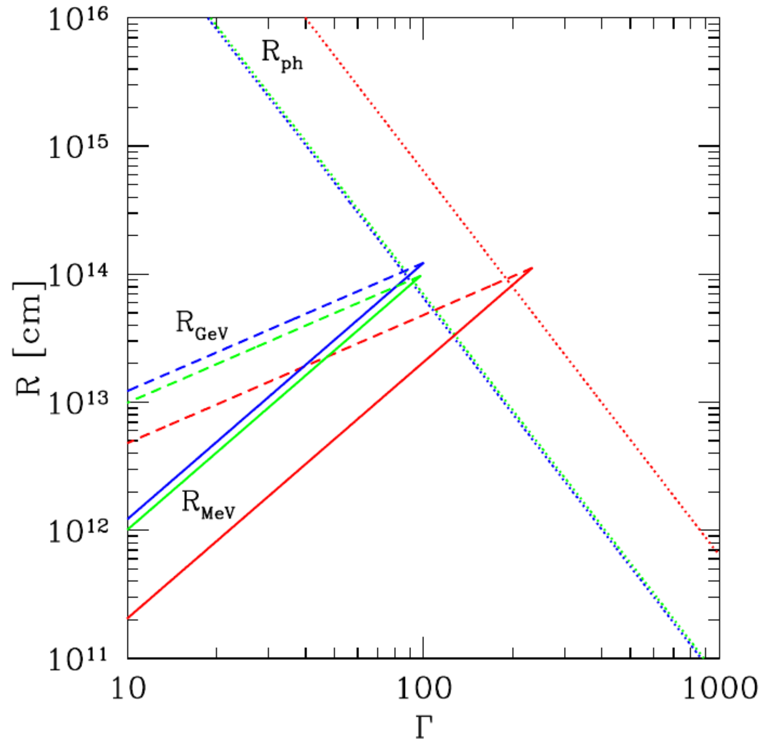
- **Temporal evolution of the high-energy break**
- **Variability**

→ Jet Lorentz factor decreases from 230 to 100 during the prompt emission

→ Emission radii R~1e14 cm

→ Internal origin of the keV / MeV / GeV emissions (e.g., synchrotron + inverse Compton)





Yassine et al. 2017, A&A 606, 93

Lorentz-Invariance Violation

- QG effects may cause violations of Lorentz Invariance (LIV)
  → speed of light in vacuum may acquire a dependence on its energy → $\upsilon_\gamma(E_\gamma) \neq c$.

- The Lorentz-Invariance violating terms are typically expanded using a series of powers of the photon energy E_γ over the *Quantum Gravity mass* M_{QG}:

$$c^2 p_\gamma^2 = E_\gamma^2 \left[1 + \sum_{n=1}^{\infty} s_n \left(\frac{E_\gamma}{M_{QG,n} c^2} \right)^n \right]$$

  where s_n={-1,0,+1} is a model-dependent factor.

- The Quantum-Gravity Mass M_{QG}
  - Sets the energy (mass) scale at which QG effects become important.
  - Is expected to be of the order of the Planck Mass and most likely smaller than it

$$M_{QG} \lesssim M_{Planck} \equiv \sqrt{\hbar c/G} \simeq 1.22 \times 10^{19} GeV/c^2$$

Lorentz-Invariance Violation

- Since $E_\gamma \ll M_{QG,n}c^2$, the sum is dominated by the lowest-order term (n) with $s_n \neq 0$, usually n=1 or 2 ("linear" and "quadratic" LIV respectively):

$$u_\gamma = \frac{\partial E_\gamma}{\vartheta p_\gamma} \simeq c\left[1 - s_n \frac{1+n}{2}\left(\frac{E_\gamma}{M_{QG,n}c^2}\right)^n\right]$$

where s_n=+1 or -1 for subluminal and superluminal speeds respectively.

- There are many models that allow such LIV violations, and some others that actually require them (e.g. stringy-foam model J. Ellis et al. 2008).

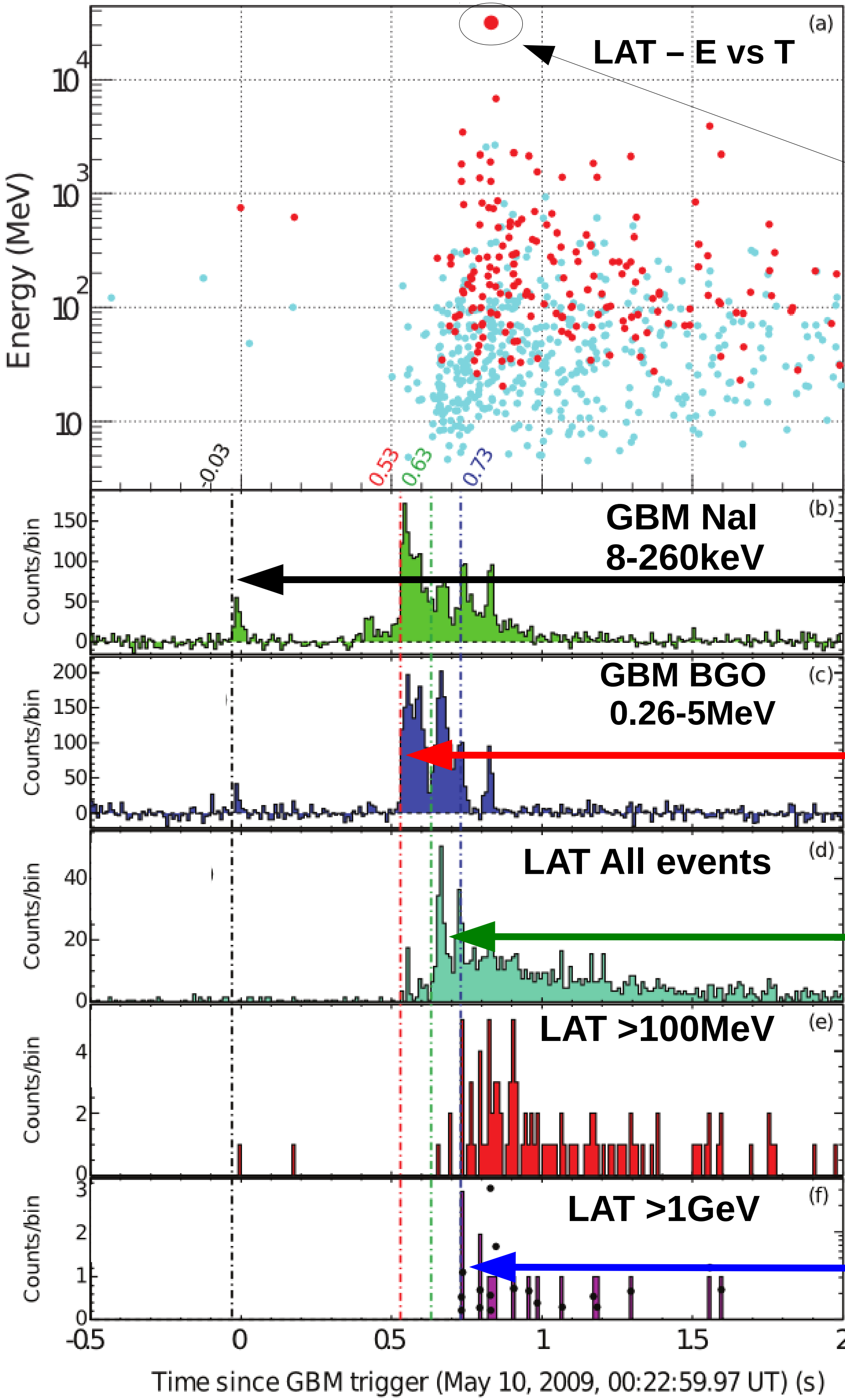
- If the speed of light depends on its energy, then two photons with energies $E_h > E_l$ emitted together will arrive at different times. For s_n=+1 (speed retardation):

$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{\mathrm{QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}\, dz'$$

- We want to constraint LIV → Set lower limits on $M_{QG,n}$

➢ We accomplish that by setting upper limits on the time delay Δt between photons of different energies.

GRB 090510



- We set upper limits on the delay Δt by associating the 31GeV photon with a *lower-energy emission interval*.
- The starting time of that interval sets an upper limit on the time delay Δt
- Most conservative case: 31GeV photon was not emitted before the start of the GRB:

  $\Delta t \leq 860\text{ms} \leftrightarrow M_{QG,1} \geq 1.19 M_{Pl}$

- Photon was emitted some time after the start of the main <MeV emission:

  $\Delta t \leq 300\text{ms} \leftrightarrow M_{QG,1} \geq 3.42 M_{Pl}$

- Photon was emitted some time after the start of the >MeV emission:

  $\Delta t \leq 178\text{ms} \leftrightarrow M_{QG,1} \geq 5.72 M_{Pl}$

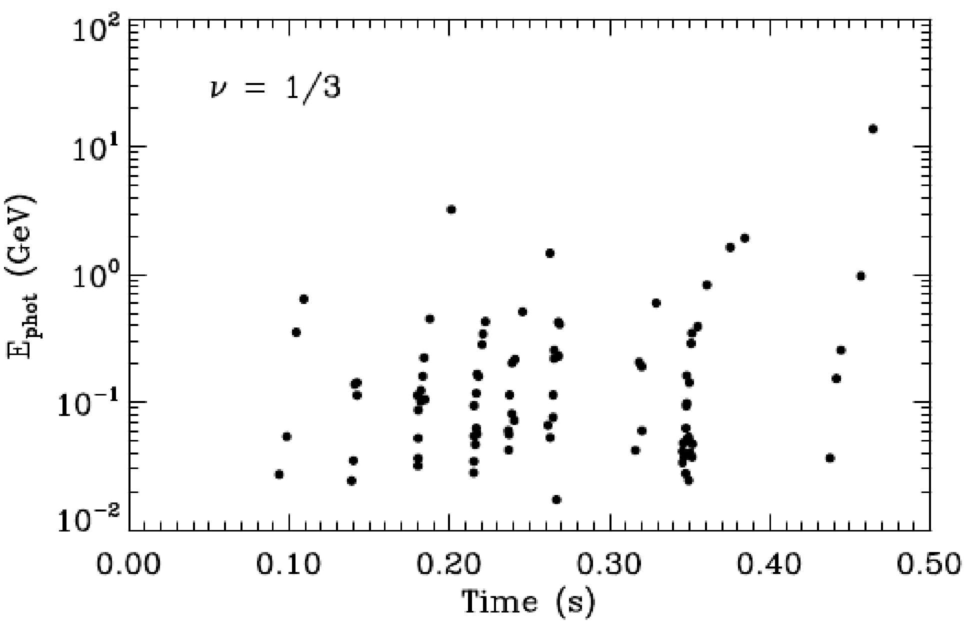
- Photon was emitted some time after the start of the >1GeV emission:

  $\Delta t \leq 99\text{ms} \leftrightarrow M_{QG,1} \geq 10.0 M_{Pl}$

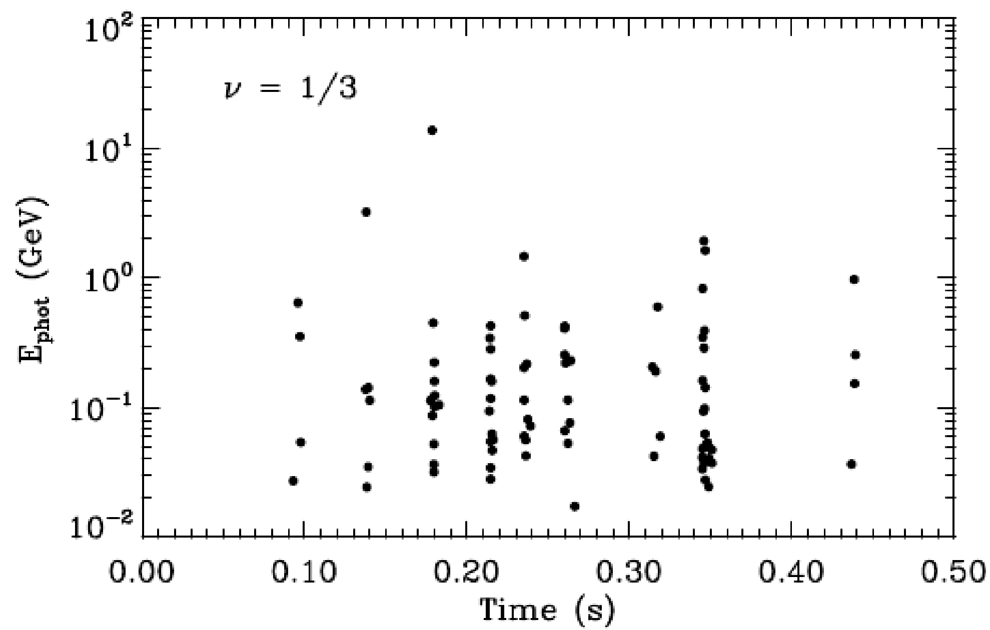
Abdo et al. 2009, Nature 462, 331

Dispersion cancellation

- Any energy-dependent time delays in our data would deform the high-energy peaks in the LAT light curve.
- We can search for the spectral-lag value that cancels any such dispersions and maximizes the sharpness of the lightcurve.
- A non-zero spectral-lag value would be a result of LIV and/or intrinsic to the GRB.



A simulated GRB light curve with a 20ms/GeV spectral lag.

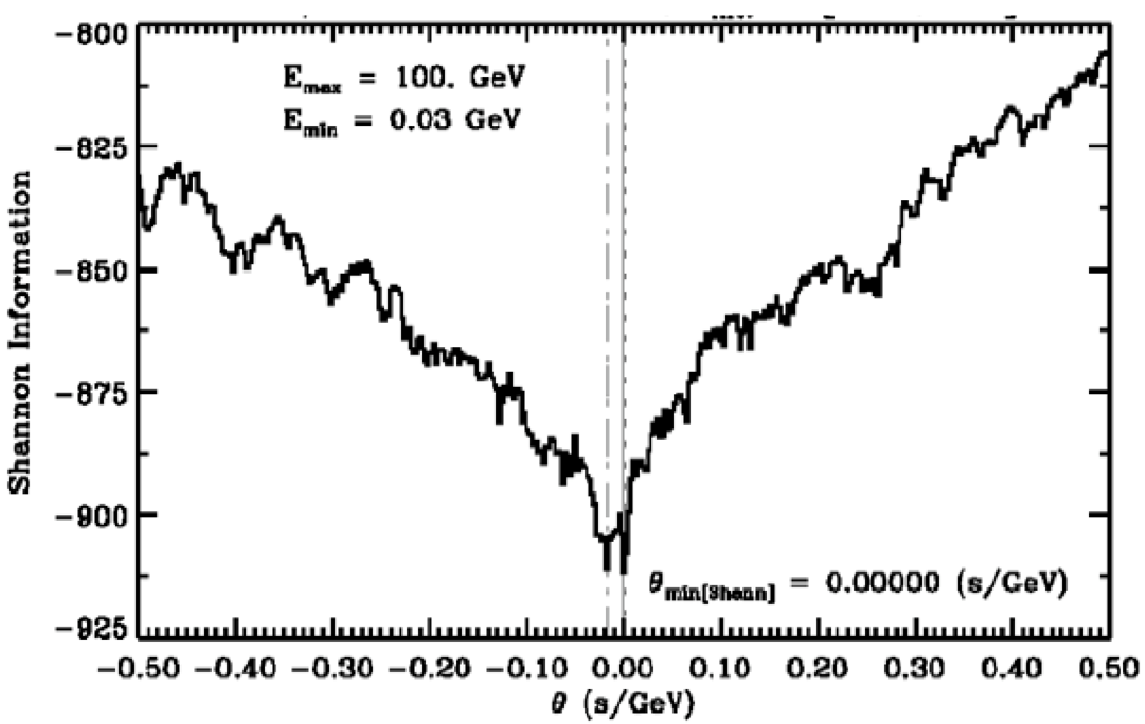


The same light curve after applying an opposite lag (peaks now maximally sharp)

Scargle J. D. et al. astro-ph/0610571v2

Finding the spectral lag

- Searched for spectral lags using all the LAT detected events (35MeV-31GeV).
- The **curve** shows a measure of the sharpness of the light curve (Shannon information) $I(\mathrm{Shannon}) = \sum_i p_i \log(p_i)$ versus the trial spectral lag.
- The s**olid vertical line** denotes the minimum of the curve, which is our effective spectral-lag measurement.
- The containment interval denoted by the **vertical dashed lines** is an approximate error region, but does not reflect statistical uncertainties.



- Our effective spectral-lag measurement:

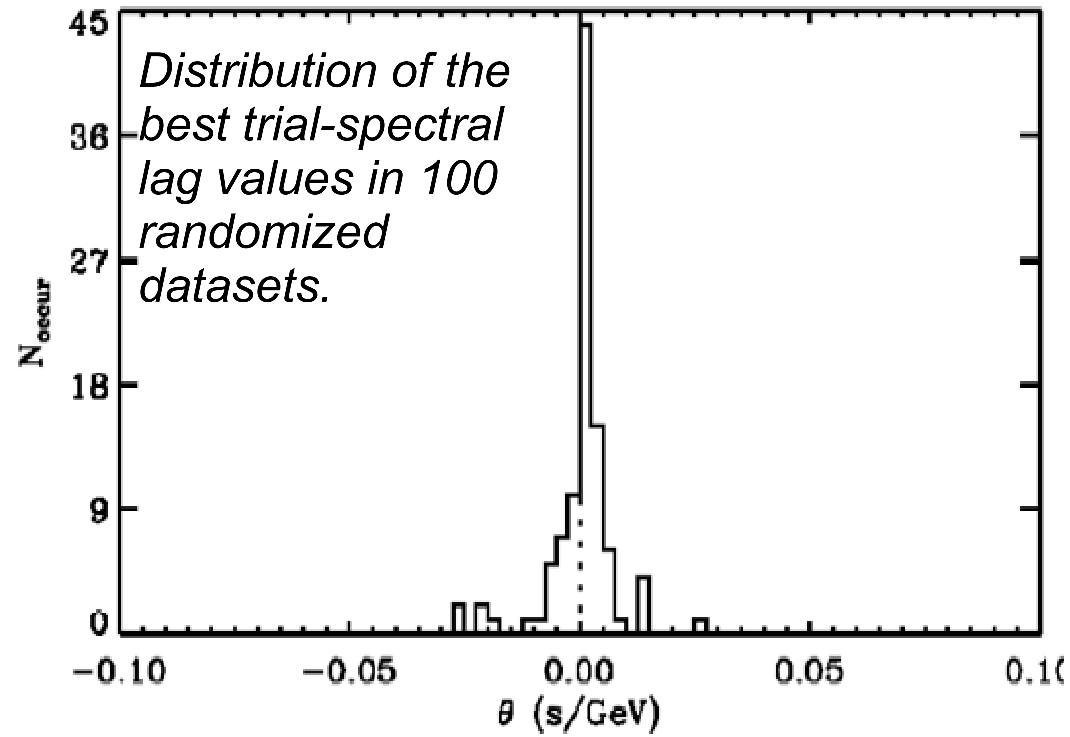
$$0^{+2}_{-18} ms/GeV$$

➔ The lightcurve was already maximally sharp.

✔ Similar results were obtained after small changes to the upper energy limit and the time interval of the used dataset.

Estimating the statistical error

- We applied the same method on randomized datasets (shuffled the times between events) to measure the uncertainty of the measured spectral-lag value.
  - 99% of the times the randomized data sets corresponded to a spectral lag smaller than ±30ms/GeV (90% of the times in ±10ms/GeV).



- Combined result: symmetric upper limit on the spectral lag coefficient:

$$|\Delta t/\Delta E| < 30\,\mathrm{ms/GeV} \leftrightarrow M_{QG,1} > 1.22 M_{Pl}$$

(99% C.L.) on possible linear (n=1) dispersion of either sign ($s_n=\pm 1$).

- Limit almost the same as the most conservative limit of the previous method.

Initial results on GRB 090510

Abdo et al. 2009, Nature 462, 331

	t_{start} (ms)	Limit on $\|\Delta t\|$ (ms)	Reasoning for t_{start} or method used for setting the limits	E_l (MeV)	Valid for s_n +1	Confidence	Limit on $M_{QG,1}$ (M_{Planck})	Limit on $M_{QG,2}$ ($10^{10} GeV/c^2$)
. (a)	-30	< 859	start of any <MeV emission	0.1	+1	very high	$\boxed{> 1.19}$	> 2.99
. (b)	530	< 299	start of main<MeV emission	0.1	+1	high	$\boxed{> 3.42}$	>5.06
. (c)	630	< 199	start of main>0.1 GeV emission	100	+1	high	$\boxed{> 5.12}$	> 6.20
. (d)	730	< 99	start of main>1 GeV emission	1000	+1	medium	> 10.0	> 8.79
. (e)	–	< 10	association with<1 MeV spike	0.1	±1	low	> 102	> 27.7
. (f)	–	< 19	if 0.75GeV γ-ray from 1st spike		-1	low	> 1.33	> 0.54
. (g)	$\|\Delta t/\Delta E\| < 30ms/GeV$		Lag analysis of all LAT photons	–	±1	very high	$\boxed{> 1.22}$	–

- We constrained small changes in the speed of light caused by linear and quadratic perturbations in (E_γ/M_{QG}).

- Using two independent techniques, we have placed strong limits on linear perturbations for both super- and sub-luminal speeds that were all higher than the Planck Mass.

- Our results support Lorentz invariance and disfavor models in which a quantum nature of space-time alters the speed of light, giving it a linear dependence on photon energy.

Improving upon the first LIV results

Vasileiou et al. 2013, PRD 87, 122001

- Used 4 GRBs all satisfying the requirements of being bright, having a measured redshift, and at least few GeV events.
  - GRBs 090510, 080916C, 090926A, 090902B

- **Analysis Methods**
  - Three methods:
    - "PairView" (PV),
      - New method developed in this work
    - "Sharpness Maximization Technique" (SMM)
      - Method similar to existing methods (e.g., DisCan, Energy Cost Function, etc.)
    - "Maximum Likelihood Analysis" (ML)
      - Existing method applied previously on LIV studies with AGN.

- Time intervals analyzed were chosen a priori such that :
  - they were not too wide to avoid too much GRB spectral evolution in the analyzed data set
  - they were not too narrow to artificially constrain the possible emission time of the GeV emission (in certain configurations this could lead to erroneously strong constraints).
- In broad terms, the analyzed data sets focused on the single brightest pulse of each GRB.

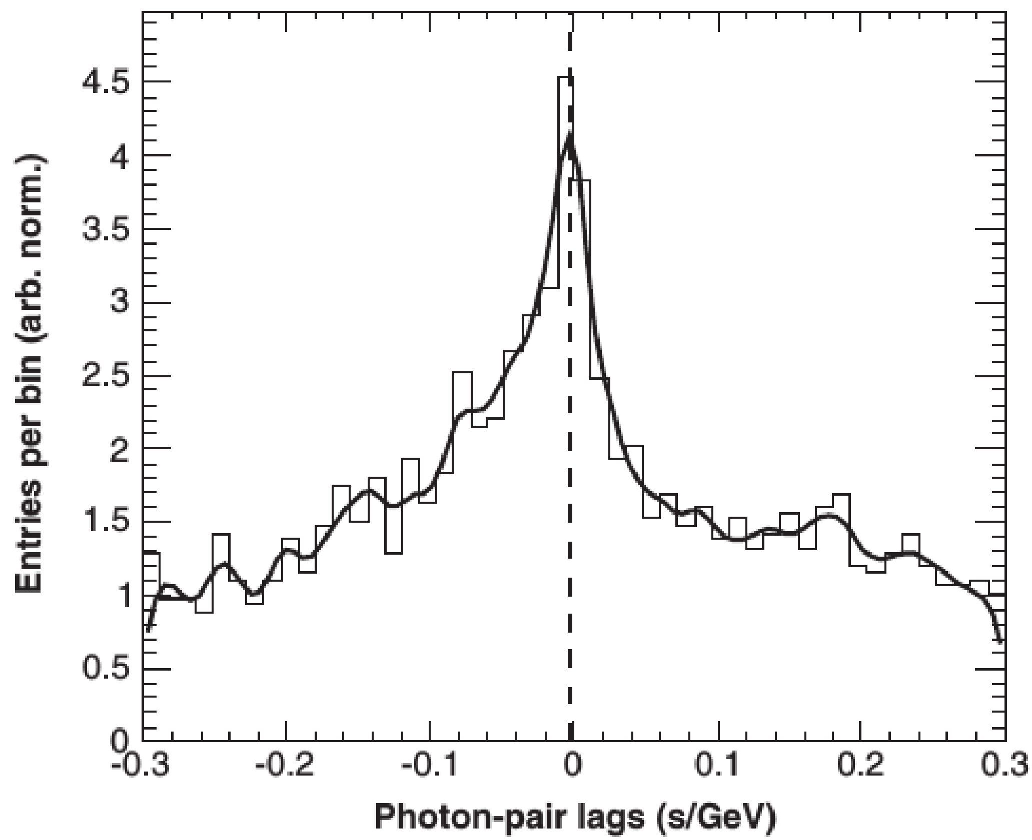
Method #1: pair view

- It calculates the spectral lags $l_{i,j}$ between all pairs of photons in a dataset and identifies the most prominent value of $l_{i,j}$ as the best estimate of the LIV parameter $\hat{\tau}_n$.

$$l_{i,j} \equiv \frac{t_i - t_j}{E_i^n - E_j^n}$$

- The distribution of $l_{i,j}$ will contain a peak approximately centered at the true value τ_n.

- From application on GRB 090510 for n=1.
- **Histogram:** distribution of photon-pair spectral lags $l_{i,j}$ (for visualization only).
- **Thick curve**: Kernel Density Estimate (KDE) of the histogram (used for finding the peak)
- **Vertical dashed line:** location of the peak of the KDE (-14 ms/GeV) used as our $\hat{\tau}_n$.



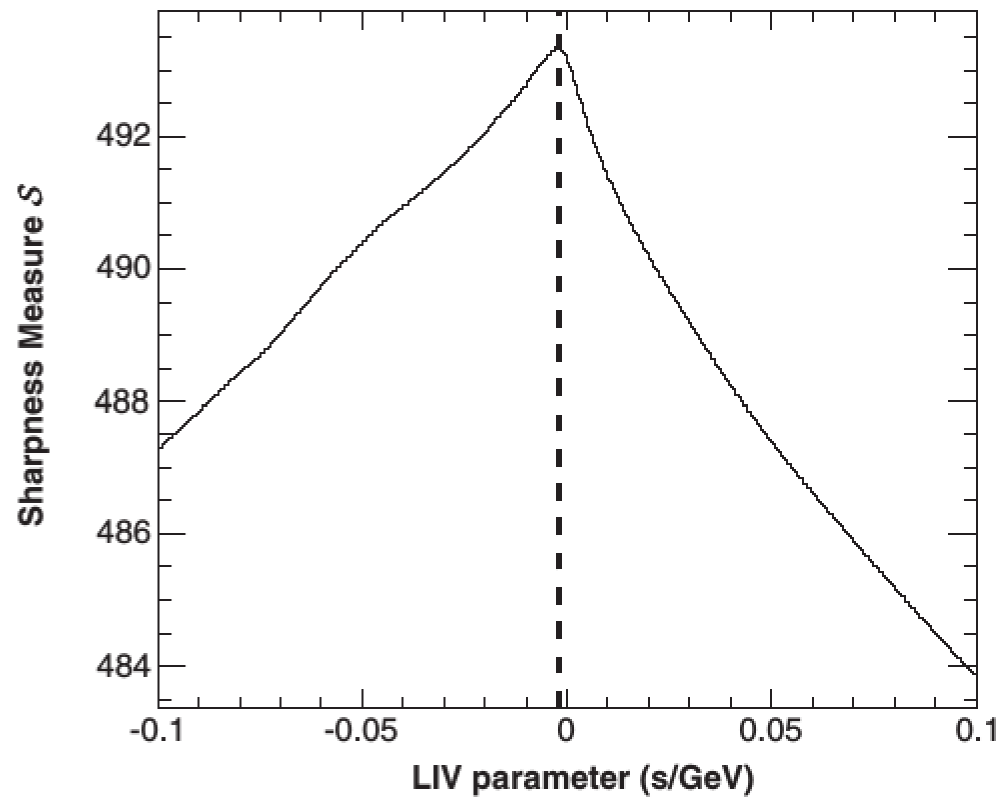
Method #2: sharpness maximization

- LIV spectral dispersion smears light-curve structure.
- Assuming signal is emitted maximally sharp →
  - search for the degree of dispersion that when it is inversely applied on the data it restores its sharpness, and use it as $\hat{\tau}_n$.
- There are multiple approaches to estimate the sharpness of the light curve:
  - DisCan (Scargle et al. 2008), Energy Cost Function (Albert et al. 2008), Minimal Dispersion Method (Ellis et al. 2008)

- Our measure of the sharpness is:

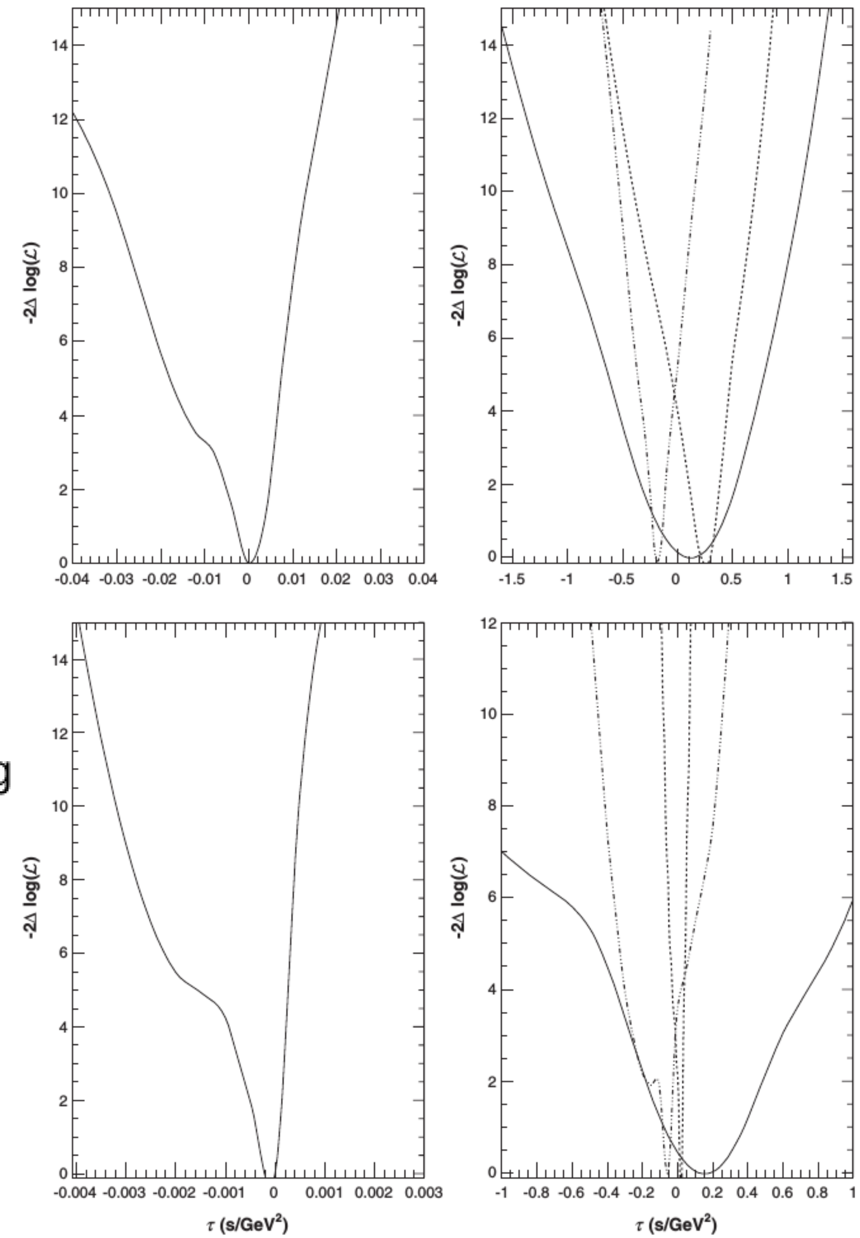
$$\mathcal{S} = \sum_{i=1}^{N-\rho} \log\left(\frac{\rho}{t'_{i+\rho} - t'_i}\right),$$

  - where t'_i is the (modified) detection time of the i^{th} photon and ρ is a configurable parameter of our method (selected using simulations).

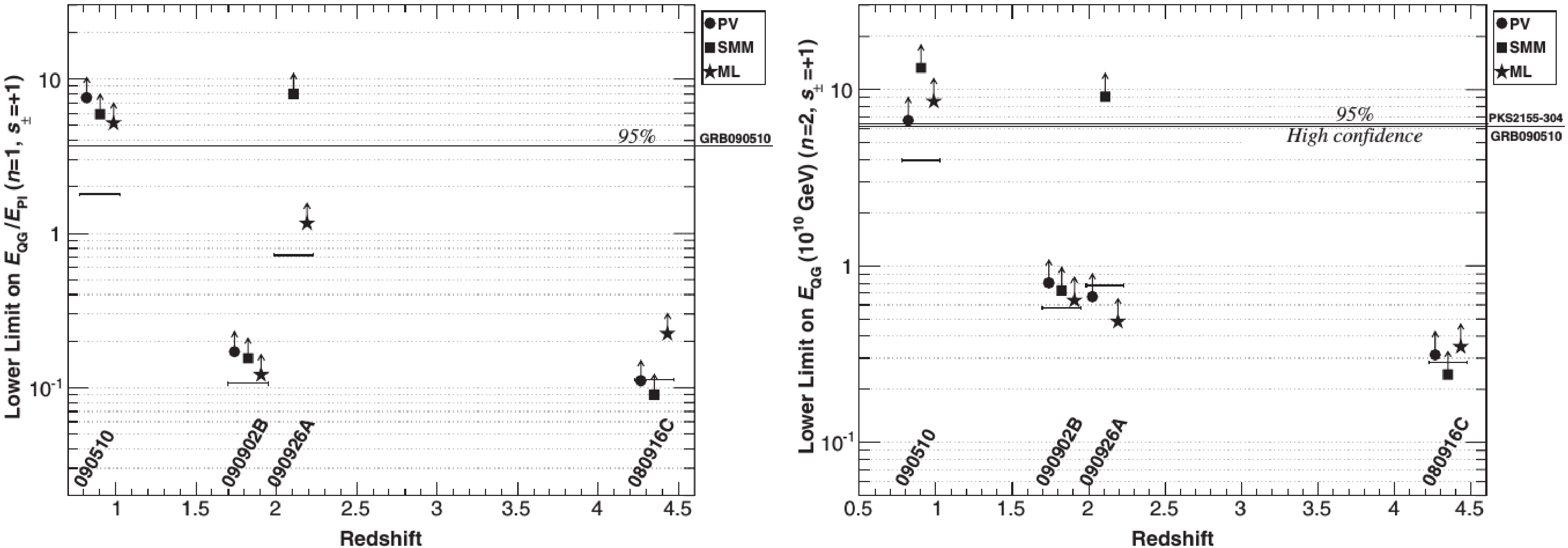


Method #3: likelihood analysis

- Existing method previously applied on LIV studies using AGN (Martinez & Errando 2009, Abramowksi et al. 2011).
- Algorithm:
  1. Derive a template of the GRB light-curve and spectrum for the case of zero LIV.
     a) Light-curve template → obtained from subset of data at low-enough energies
     b) Spectral template → obtained from data as-is assuming that LIV does not distort spectrum in a statistically-significant degree.
  2. Calculate an unbinned likelihood function that describes the probability of detecting each of the photons (i.e., their time and energy) in the data given our model of the data (from step #1) modified according to some dispersion described by a τ_n.
  3. Maximize the likelihood to estimate $\hat{\tau}_n$.
  4. Calculate confidence intervals on τ_n by repeating steps 1—3 on simulated data sets.



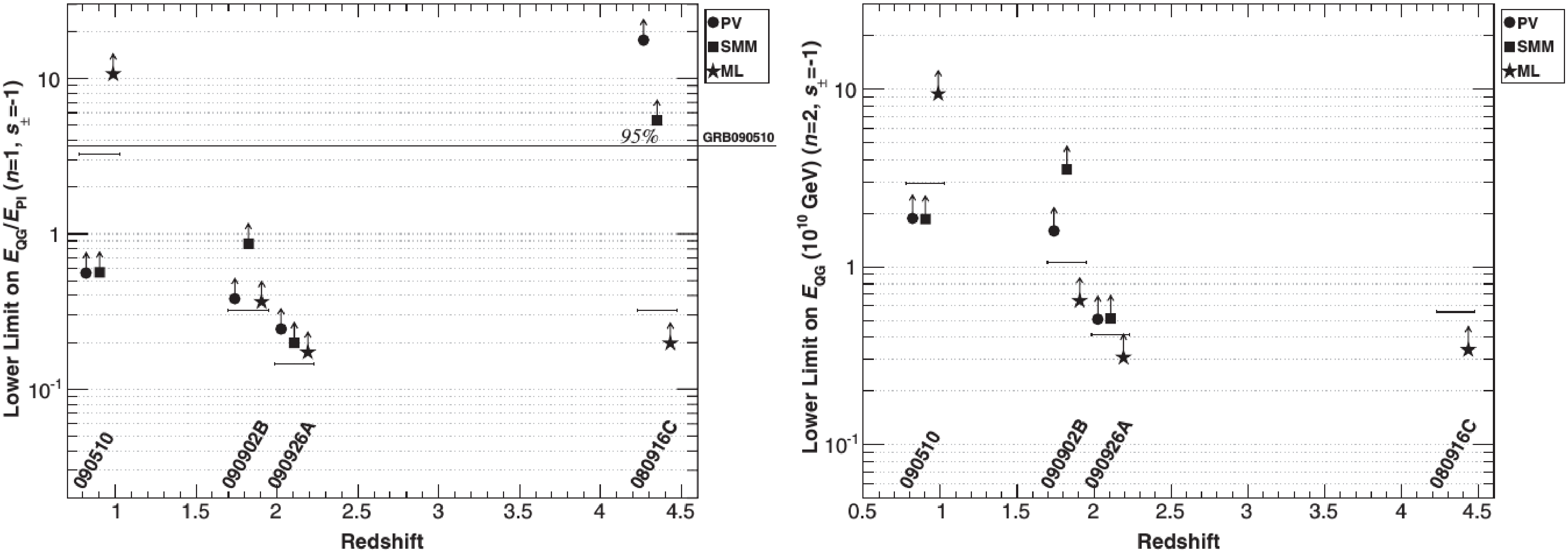
95% lower limits (subluminal case)



Vasileiou et al. 2013, PRD 87, 122001

- Each triplet of markers corresponds to a GRB
- Markers inside each triplet show our constraints using τ_n (with no correction for GRB-intrinsic spectral evolution effects) by PV, SMM, ML.
- Horizontal bars show our constrain averaged over the three methods using τ_{LIV} (allowing for the possibility of intrinsic effects)
- Horizontal lines show current most robust and constraining limits
  - GRB 090510 → Fermi LAT and GBM Collaborations (Abdo et al. Nature, 462, 2009)
  - PKS 2155-304 → H.E.S.S. (Abramowski et al., Astroparticle Phys. 34, 2011)
- We improve existing 95% limits by factor of ~2 for n=1 and n=2
  - n=1: $E_{QG} \gtrsim 8\ E_{Pl}$ (improvement by factor of ~4 at 99% CL)
  - n=2: $E_{QG} \gtrsim 1.3\times10^{11}$ GeV

95% lower limits (superluminal case)



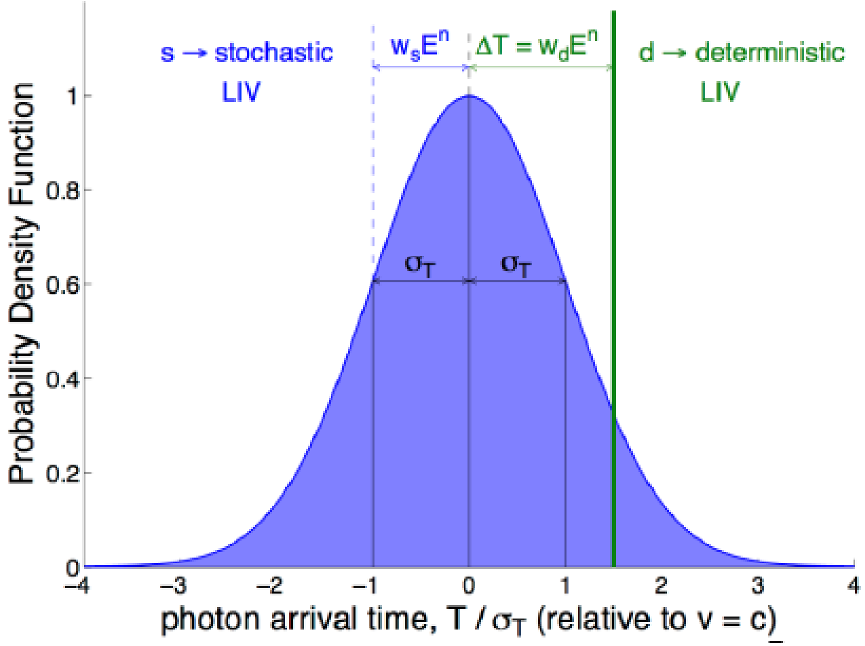
Vasileiou et al. 2013, PRD 87, 122001

- Legend same as previous slide.
- We improve n=1 limits by Fermi by factor of ~3.
- No robust limits that I know of for n=2

Stochastic LIV with GRB 090510

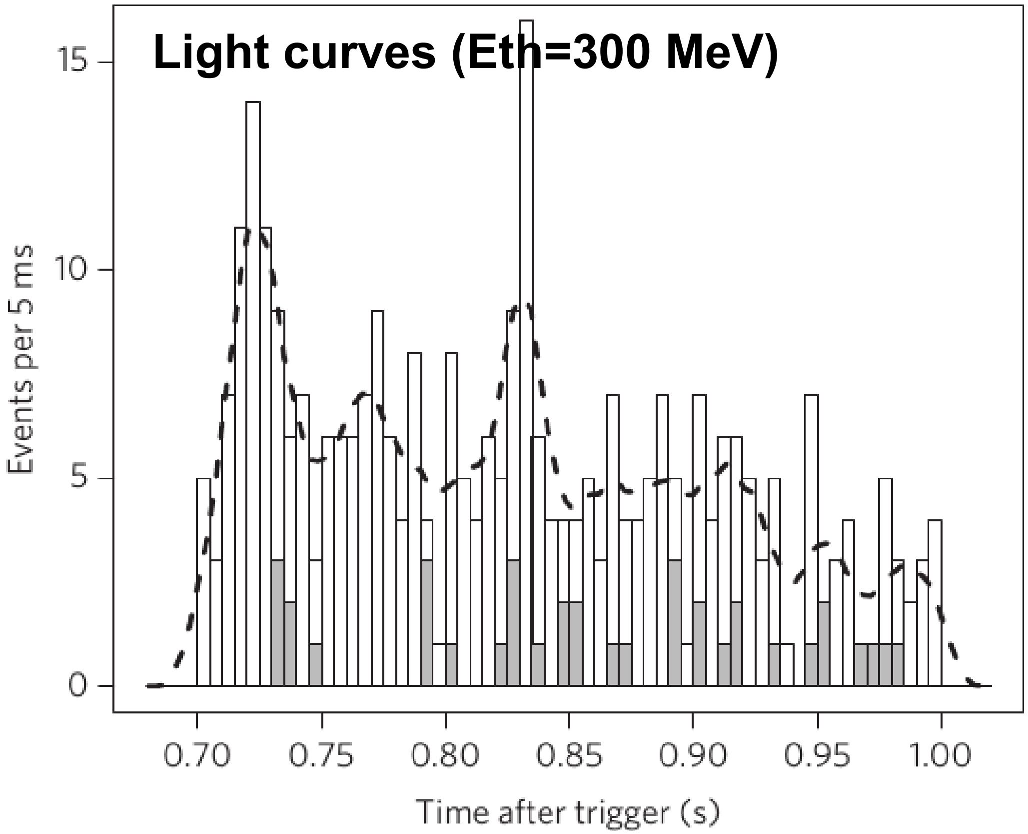
- **Purpose**: Produce a robust and comprehensive set of constraints on fuzzy LIV.
- Fuzzy/stochastic LIV:
  - The dispersion effect per photon is random, following some PDF that extends to both positive and negative values.
  - We consider LIV linear in E and use a Gaussian PDF centered around v = c, i.e.
    - $P(v) = \mathrm{Norm}(\mu = c, \sigma_v = (c/T)*w*E)$ (T = effective travel time from source for v = c)
    - $w \propto 1/E_{QG}$ (in s/GeV)
      - » w is the parameter to be constrained
      - » describes magnitude of LIV effect
  - effect averaged over all photons is ~zero
  - effect per photon can be either "acceleration" (v > c) or "deceleration" (v < c)
- Manifested as energy-dependent broadening of pulses (deterministic LIV is manifested as energy-dependent skewing of pulses).
- **Method:**
  - Maximum likelihood analysis (MLA)

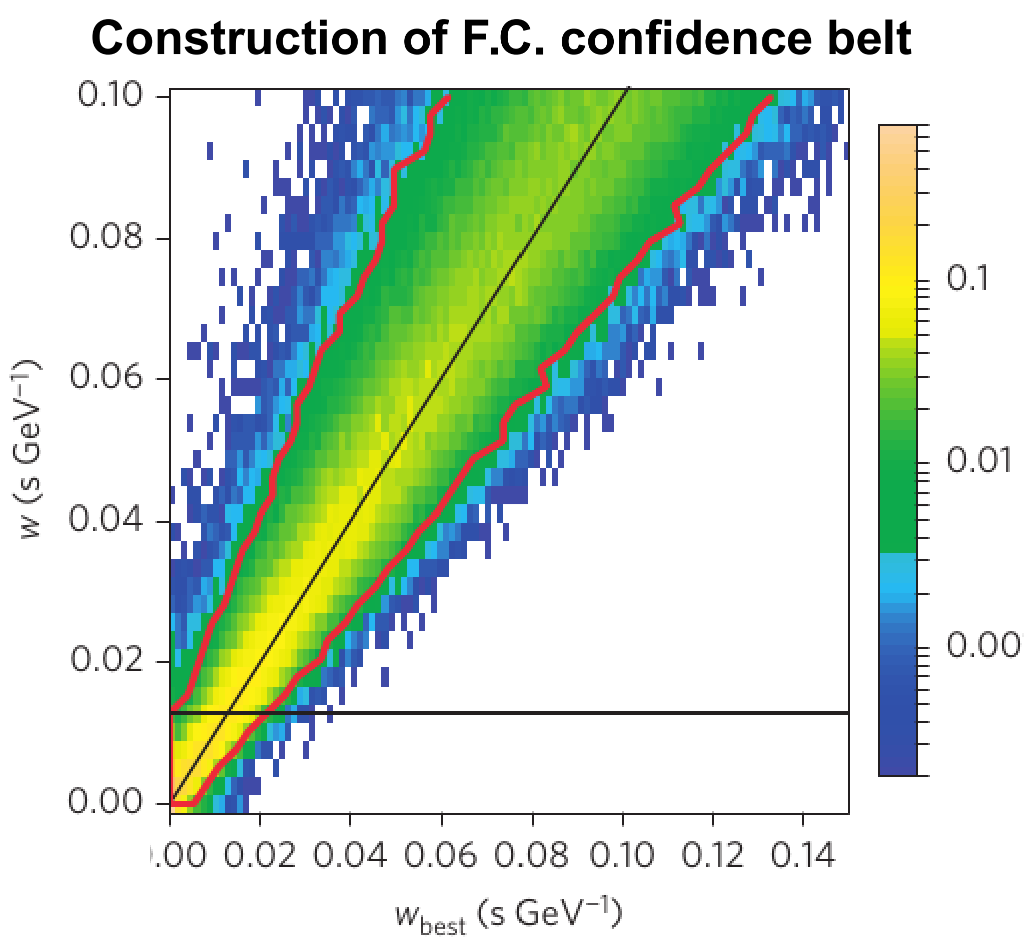
Arrival time distribution for a delta function emission



Vasileiou et al. 2015, Nature Physics 11, 344

Stochastic LIV with GRB 090510





- Best estimate on w = 0 s/GeV
- Upper limits on w
  - 95% w < 0.013 s/GeV or $E_{QG,1}$ > 2.8 E_{Planck}
  - 99% w < 0.023 s/GeV or $E_{QG,1}$ > 1.6 E_{Planck}
- We set, for the first time ever, a limit on $E_{QG,1}$ for stochastic LIV above the Planck mass.
- We also set limits on the corresponding length scale:
  - 95% $L_{QG,1}$ < 0.71 L_{planck}
  - 99% $L_{QG,1}$ < 1.3 L_{planck}

Vasileiou et al. 2015, Nature Physics 11, 344

Summary & conclusions

- **GRB population studies at high energies are now possible with *Fermi***
  - GRB >100 MeV emission is delayed & temporally extended w.r.t. the emission in the keV--MeV range
- **Prompt emission phase observed over a wide energy range**
  - Complex spectral shapes are needed to reproduce the spectrum
  - Broad-band physical models are a pre-requisite to understanding GRB high-energy emission
  - Origin of the delayed onset of the LAT >100 MeV emission?
  - Understanding the transition from the prompt emission phase to the early phase is of great importance
- **Long-lived GeV emission is consistent with the canonical afterglow model**

- **Four GRBs detected by LAT to produce robust and stringent constraints on LIV**
- **Methodology**
  - Three different and complementary techniques – one of them brand new
  - The techniques used the full range of statistics instead of a single event
- **We improved the existing limits for both linear and quadratic LIV**
  - Also constrained the superluminal quadratic case (first such result I know of)
  - The limits from the other 3 GRBs are all also quite strong, for most of the cases ~an order of magnitude within E_Planck

- **Our results disfavor any class of models implying LIV below or right above the Planck scale**